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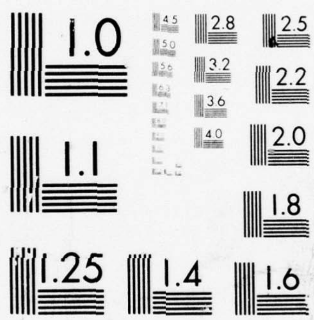
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# NAVY LABORATORY INTERACTIVE GRAPHICS STUDY FINAL REPORT

by
Dale Oliver Christensen
Interactive Graphics Program
*Fuze and Sensor Department*
for
Dr. James H. Probus
Director of Laboratory Programs

MARCH 1979



**NAVAL WEAPONS CENTER**
**CHINA LAKE, CALIFORNIA 93555**

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# Naval Weapons Center
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## FOREWORD

The use of minicomputer-based turnkey interactive graphics systems has increased significantly at the Navy laboratories. Between 1975 and 1978, three systems were procured by different Navy laboratories. In late fiscal year 1977, the Director of Laboratory Programs approved the funding of a Navy Laboratory Interactive Graphics Study for fiscal year 1978 to determine the Navy laboratories' interactive graphics needs.

The Navy Laboratory Interactive Graphics Study was funded by the Director of Laboratory Programs from the RDT&E,N appropriation, program element 65861N, project Z0832.

This report is the final report to the Director of Laboratory Programs for the Navy Laboratory Interactive Graphics Study.

Released by
R. A. BOOT, *Head*
*Fuze and Sensors Department*
16 January 1979

Under authority of
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(U) *Navy Laboratory Interactive Graphics Study, Final Report,* by Dale Oliver Christensen. China Lake, Calif., Naval Weapons Center, March 1979, 42 pp. (NWC TP 6083, publication UNCLASSIFIED.)

(U) The objective of the Navy Laboratory Interactive Graphics Study (NLIGS) was to define the interactive graphics needs of the Navy laboratories in the present and in the future. In this study, interactive graphics refers to the minicomputer-based turnkey interactive graphics systems (MTIGSs).

(U) The seven Navy laboratories formally requested a total of 110 work stations under NLIGS. The application areas are documentation and drafting, mechanical design and layout, integrated circuit design, design and fabrication of printed circuit boards, and tape preparation for numerical control machines.

(U) The recommendations of the NLIGS are that $10M in funds be identified over a 2-fiscal-year period to procure a Navy laboratory MTIGS, that a support organization be established to increase overall system productivity, that a productive study be initiated to develop the methods of monitoring system productivity, that each Navy laboratory submit an interactive graphics implementation plan, and that a national graphics information interchange standard be pursued.

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# INTRODUCTION

Over the past 5 years, there has been a growing interest in minicomputer-based turnkey interactive graphics systems (MTIGSs). The term *interactive graphics* refers to a computer-based system that stores, displays, and manipulates information in a digital data base. These manipulations include modeling, preprocessing information for analysis programs, preparing formal documentation, outputting to a computer output microfilm (COM) device, and preparing control tapes for numerical control (N/C) machines. Using conventional methods, these functions are handled individually. In a digital data base, all these functions have a common source. The combination of the common source and the software, which has been tailored to complete a specific function, has shown impressive manpower productivity increases.

There are three major types of interactive graphics systems: host-computer-based systems, minicomputer refresh systems, and MTIGSs.

The host-computer-based interactive graphics systems are generally very expensive to use and require a large host computer dedicated to graphics. The minicomputer refresh systems are used primarily in simulators where the hardware is very sophisticated, but the user is required to write most of his own software. Since most simulation requirements are unique, software must be written by someone thoroughly knowledgeable with the application. For MTIGSs, the vendor provides all the hardware and software in an integrated package. It is minicomputer based and is a stand-alone system. This study, the Navy Laboratory Interactive Graphics Study (NLIGS), is concerned only with MTIGSs.

In the early 1970 s, MTIGSs were primarily used to prepare documentation of printed circuit boards (PCBs). As the software has been developed, many other areas have been added. These include modeling, analysis preprocessors, output to computer output microfilm, and N/C tape preparation. The vendors are in a very competitive market, and the sophistication level of the software is progressing rapidly. In the next 5 years, the modeling, analysis preprocessors, and N/C tape preparation capabilities will be greatly extended.

The Navy laboratories (NLs) have had an interest in MTIGSs since 1973. The microelectronics group at Navy Electronics Laboratory Center (now Naval Ocean Systems Center (NOSC)), San Diego, California, was the first to procure an MTIGS. It is used exclusively for integrated circuit design. A Computervision system was procured and installed in 1974. In 1975 both the Naval Weapons Center (NWC), China Lake, California, and Naval Ordnance Laboratory (now Naval Surface Weapons Center (NSWC)), White Oak, Maryland, started writing specifications to procure MTIGSs. Both NWC and NSWC required a general-purpose system with the application areas of documentation preparation, PCB design, and N/C tape preparation. An Applicon system was procured and installed at NWC in January 1977. A Computervision system was procured and installed at NSWC in February 1978.

With the growing interest of many of the NLs for MTIGS, the Director of Laboratory Programs (DLP) tasked NWC to conduct the NLIGS in FY 78.

This final report documents the results and recommendations of the NLIGS.

# OBJECTIVE

The objective of the NLIGS is to define the NL MTIGS needs for the present and future. If the study results showed the need for MTIGSs in the NL community, a large competitive procurement would be conducted. Funding would be provided by the DLP. The initial and updated NLIGS proposals are given in Appendix A.

# APPROACH

## INITIAL ACTION

The study began in October 1977. A milestone chart and schedule for the study are shown in Figure 1. The first milestone was to establish a contact point at each NL. This was completed in November 1977. A list of the contact point personnel is in Table 1. NLIGS personnel felt that it was very important that each NL determine its own needs using its own personnel. Assistance from the NLIGS principal investigator was available.

Since the MTIGS industry is very dynamic, an ongoing vendor or market survey will continue throughout the program. Semi-annual contacts have been made and are being continued with the major MTIGS vendors.

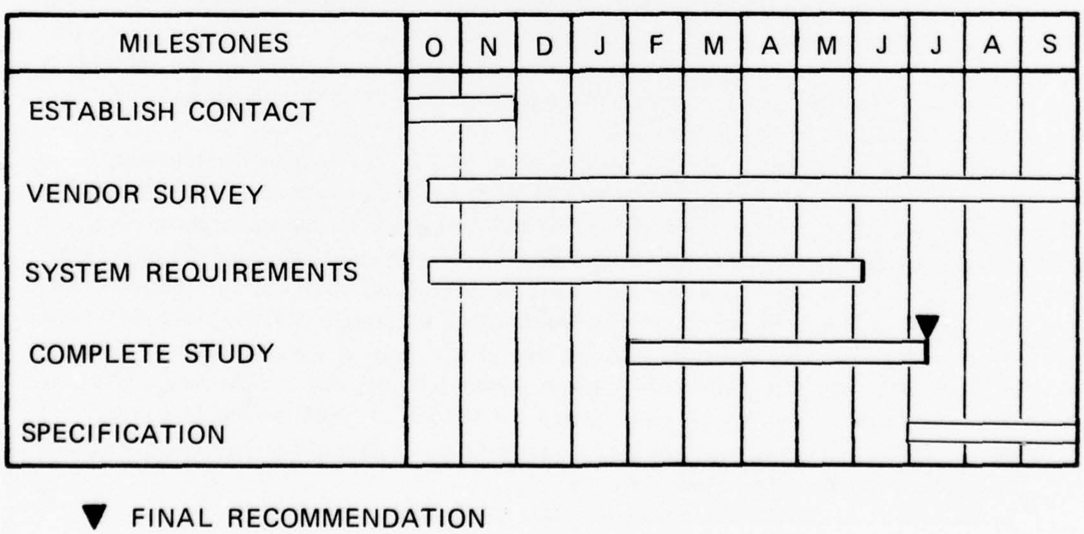



FIGURE 1. Interactive Graphics Study Milestones (FY 78).

TABLE 1. NLIGS List of Contact Point Personnel.

| Laboratory | Contact |
|---|---|
| NADC | Daniel R. Tarrant |
| NCSC | Paul C. Bishop |
| NOSC | Pat D. Burke |
| NSRDC | Ruey Chen |
| NSWC | |
| DL | Carrol T. Shelton |
| WO | Carl A. Nelson |
| NUSC | |
| NLN | H. Gerry Lipsett |
| NPT | Thomas A. Galib |
| NWC | Dale O. Christensen |
| | John E. Anderson |

The NLIGS principal investigator made three visits to each NL during FY 78. He briefed interested parties about the potential application areas for MTIGSs. The interested personnel and the contact point, along with the help of the local Navy Laboratory Computer Committee (NLCC) representative, then submitted their requirements to the NLIGS principal investigator.

A meeting of NLIGS contact point personnel was held at NWC in February 1978. The purpose of that meeting was to agree on ground rules for the NLIGS cost justification format. The cost justification assumptions are given below. A discussion of these justifications is in Appendix B. Other milestones for FY 78 included the writing of this document and starting the preliminary specification.

## COST JUSTIFICATION ASSUMPTIONS

The following assumptions were made at the outset of this study:

1. Only quantifiable dollar savings would be considered (see Appendix B).
2. Quality of the manual and automated produced drawings would be directly compared.
3. The application areas for the NLs were limited to documentation preparation, mechanical design, and simple CAD/CAM applications–PCB generation, N/C tape preparation, and Integrated Circuit (IC) design.
4. A 5-year system life was assumed.
5. A 2:1 productivity increase with no support organization over all application areas for the system life was assumed.
6. The price of a system was estimated at $100K per work station.
7. The present work load in the applications areas was assumed to be constant over the next five years.
8. A cost analysis was to be prepared by each NL using the fast payback format according to NAVCOMPINST 7000.38, Attachment 1.

# RESULTS OF THE STUDY

Documentation is one of the most cost-effective applications for MTIGSs. Because every NL has a large documentation requirement, each NL has a legitimate need for an MTIGS. The number of work stations requested varies with the size of the laboratory and the number of application areas. A total of 110 work stations was requested by the seven NLs. A list of requested work stations and cost savings by laboratory is given in Table 2. The application areas for each laboratory are given in Table 3.

TABLE 2. NLIGS Work Station Requests and Estimated Cost Savings.

| Laboratory | Requested work stations | Savings, $K* |
|---|---|---|
| NADC | 8 | 1,261 |
| NCSC | 5 | 640 |
| NOSC | 10 | 1,580 |
| NSRDC | 10 | 2,530 |
| NSWC | | |
| DL | 9 | 1,712 |
| WO | 5 | 814 |
| NUSC | | |
| NPT | 17 | 1,652 |
| NLN | 22 | 3,092 |
| NWC | 24 | 5,824 |
| Total | 110 | 19,105 |

*Does not include equipment cost.

TABLE 3. NLIGS Application Areas by Navy Laboratory.

| Area | Laboratory | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | NADC | NCSC | NOSC | NSRDC | NSWC | | NUSL | | NWC |
| | | | | | DL | WO | NLN | NPT | |
| Documentation | | | | | | | | | |
| Piece Part | X | X | X | X | X | X | X | X | X |
| Assembly | X | X | X | X | X | X | X | X | X |
| Updates | X | X | X | X | X | X | X | X | X |
| COM | X | | | | | | | | X |
| Mech Design | | | | | | | | | |
| LAD | X | X | X | X | X | X | X | X | X |
| TOL Study | X | X | X | X | X | X | X | X | X |
| Electrical | | | | | | | | | |
| PCB | X | X | X | X | X | X | X | X | X |
| N/C | | | X | X | X | X | | | X |
| IC | | | X | | | | | | |

Notes: LAD – Layout and Arrangement Drawing
TOL – Tolerance
N/C – Numerical Control (Machine Tools)

# DISCUSSION OF RESULTS

## NUMBER OF WORK STATIONS

The number of work stations requested by each NL was given in Table 2. NADC, NOSC, NSRDC, and NSWC/DL requested about 10 work stations apiece, NCSC (the smallest NL) requested five. The existing system at NSWC/WO plus the work stations requested will also total 10 work stations, for that NL. Both NUSC/NPT and NUSC/NLN have very large documentation requirements for their eight product lines. This accounts for their asking for a total of 39 work stations. NWC requested 24 work stations. Since NWC has an existing system, many more people have been exposed to the MTIGS capabilities and want to expand their usage.

## APPLICATION AREAS

The application areas (see Table 3) are very similar for all the NLs; a more detailed discussion of the MTIGS application areas is given in Appendix C.

All of the work stations will be used in five primary application areas. Each NL has requirements for generating documentation, including piece part and assembly drawings, and for updating drawings. (The creating and updating of documentation is one of the most cost-effective application areas of MTIGSs.) The most sophisticated software has been developed for the PCB application area, and almost every laboratory has a requirement in this area. Finally, all the laboratories indicated a use for MTIGSs in the area of mechanical design layouts and arrangement drawings, a powerful application area. Five of the NLs also want to use MTIGSs for developing and preparing tapes for N/C machines tools. At present 2–1/2- and some 3-axis N/C machines can be accommodated. NOSC will use the MTIGS for IC design.

## COSTING PLANS

Seven different cost plans and the cost analysis assumptions for procuring an NL MTIGS are given in Table 4. (The details of each plan are given in Appendix D.) The two major variables are funding levels and a support organization function. The funding levels are at $10M, $8.5M, and $6M. Plans 1, 2, and 3 include a support organization, and plans 4, 5, 6, and 7 do not. The number of work stations per plan per NL is given in Table 5.

TABLE 4. NLIGS Cost Analysis (Five-Year Period).

| Factor | Plan | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| No. of work stations | 115 | 97 | 55 | 110 | 11.0 | 92 | 50 |
| System cost, $M | 10.0 | 8.0 | 6.0 | 9.8 | 9.8 | 7.8 | 5.8 |
| Gross savings, $M | 26.3 | 19.9 | 5.6 | 19.1 | 15.3 | 11.6 | 3.5 |
| Net savings, $M | 16.3 | 11.9 | (0.4) | 9.3 | 5.5 | 3.8 | (2.3) |

Notes: 1. Plan 4 information came from each NL;
Plans 1, 2, 3, 5, 6, and 7 were derived from Plan 4
2. Assumptions:
All Plans:
Five-year system life
Constant FY 78 dollars
One man-year labor per work station
Enough work to fill work station for 1 shift/work day
Support cost same for all plans
Maintenance = $10K per work station per year
Plans 1, 2, 3
Support Organization
2.6:1 Productivity Increase
Plans 5, 6, 7
No Support Organization
2.0:1 Productivity Increase

TABLE 5. Suggested Work Stations by Plan.

| Lab | Plan 1 | 2 | 3 | 4,5 | 6 | 7 |
|---|---|---|---|---|---|---|
| NADC | 8 | 7 | 4 | 8 | 7 | 4 |
| NCSC | 5 | 4 | 3 | 5 | 4 | 3 |
| NOSC | 10 | 9 | 5 | 10 | 9 | 5 |
| NSRDC | 10 | 9 | 5 | 10 | 9 | 5 |
| NSWC | | | | | | |
| DL | 9 | 8 | 5 | 9 | 8 | 5 |
| WO | 5 | 4 | 3 | 5 | 4 | 3 |
| NUSC | | | | | | |
| NPT | 17 | 15 | 8 | 17 | 15 | 8 |
| NLN | 22 | 18 | 8 | 22 | 18 | 8 |
| NWC | 24 | 18 | 9 | 24 | 18 | 9 |
| SC | 5 | 5 | 5 | — | — | — |
| Total | 115 | 97 | 55 | 110 | 92 | 50 |

Defining system costs is difficult, because the electronics industry is so dynamic. The microprocessor is significantly impacting the MTIGS industry. The manufacturers of MTIGSs do not know the details of the equipment that they will be selling 18 to 24 months from now; they know about 12 to 18 months in advance. This has made it very difficult to calculate system costs. Today's prices have been used to calculate system costs. The manufacturers indicate that more powerful work stations will be available in the future for about the same price as today's equipment.

A new generation of MTIGS work stations is coming in FY 79; and in FY 80, a new generation of MTIGS central systems is predicted. The move for the new central system will be toward a distributed processing network. The proposed NLIGS procurement will include the new generation work stations and central systems.

The issue of cost savings is important to this study. The cost and savings factors used in this study were selected with great care. Small changes in productivity are associated with large dollar savings. A cost sensitivity analysis was performed to see the effect of different productivity figures (see Appendix E). An increase in the productivity of 0.1 for plan 1 results in an additional $2.67M savings over the life of the system.

The net savings (gross savings minus system cost) bring out an interesting point: there is a significant support overhead associated with the system. For example, looking at plan 1:

| | | | |
|---|---|---|---|
| Manual Labor | $69.5M | MTIGS Labor | $26.7M |
| Support Overhead | 0.3M | Support Overhead | 16.3M |
| | $69.8M | | $43.0M |

The support overhead in the manual method accounts for 0.4% of the total cost. Using an MTIGS, support overhead accounts for 37.9% of the total cost. The MTIGS support overhead pays for indirect labor to operate the system, the system maintenance, and the support organization function, if applicable. Due to this large overhead, plans 3, 6, and 7 do not fare as well as the other plans. The evaluation of the net savings figures is straightforward; plans 1 and 2 are the most cost effective.

The difference in equipment between plans 1 and 2 is more than just 18 MTIGS work stations; other peripheral hardware has also been deleted. If the largest net savings is the criterion for selection, plan 1 should be implemented. (System payback will be about two years for plan 1.)

Because of uncertainty of inflation factors over the five-year period from FY 81 to FY 85, constant FY 78 dollars are used. The figures are shown for a 5-year period, assuming an average productivity for the period of time. In real life, there is a productivity curve. A 2:1 productivity is assumed if there is no support organization, and 2.6:1 productivity if there is a support organization.

In order to better quantify interactive graphics system productivity, an effort should be undertaken to monitor present productivity increases at the interactive graphics facilities located at NWC and NSWC/WO. This effort would develop the necessary techniques to monitor interactive graphics system productivity after its installation in the NLs.

## IMPLEMENTATION PROBLEMS

The ultimate goal of MTIGS is to help increase productivity to the highest possible level. Interactive graphics is a highly productive tool, but experience has taught that there are ways to increase and maximize productivity gains.

There are a number of MTIGS problem areas that need to be addressed. These problem areas include duplication of effort, standardization, documentation, training, software testing, future planning, and networking. To deal effectively with all these problems, manpower is needed to solve the problems.

Sandia Laboratories in Albuquerque, New Mexico, has one of the premier software organizations in the MTIGS industry user base. NWC has also received software from Sandia Labs and implemented it. The Sandia-developed software has brought NWC by far the highest productivity gains. (NWC uses the Sandia software package for generating electrical schematics.) Productivity constants from 2:1 to 4:1 have been quoted by the NWC users for schematic creation.

Two of the most serious problems that will face the NLs as a result of the installation of a large, networked MTIGS will be duplication of effort and standardization. The MTIGS vendor provides the system software commands to create the geometry, manipulate the graphics, and handle the files. What is missing are the component libraries and standardized graphics techniques built into an application package which can be simply utilized by the system operators. These applications packages have to be tailored to the individual needs of each installation. A two-step approach is required. The support organization meets the first step, and the local organization meets the second step. (A discussion of support and local organizations is in the next two sections.)

With the installation of an MTIGS, work must begin immediately to develop the menus, macros, component libraries, and other tailored software necessary for each application area. Initially, at NWC, the people who learned the system first developed the standards and application packages. This was a very slow and painful process. Since revisions of the system software come out every 6 to 8 months, the application packages need to be updated to take advantage of new system features. In some cases, this

requires major revisions to these application packages. As the application packages change, new documentation of these packages is also required. All the operators need to be updated in the use of these new packages. These are not trivial changes and manpower is needed to implement them.

The system software as it comes from the vendors has errors in it. Before these application packages can be implemented, the software must be tested and alternate approaches developed. Networking of all the NLs using the Navy Laboratory Computer Network (NALCON) will also create problems. The interfacing of the NL MTIGS into the national standards effort also must be addressed.

## SUPPORT ORGANIZATION

If all of the above problems are handled on a local basis, each NL will approach them differently. There will be ten times the people working on the problems. Instead of being productive on the system, they will be addressing the above-mentioned problems. A support organization could deal with these problems, allowing local personnel to continue at a productive level. A proposed support organization chart is given in Figure 2.

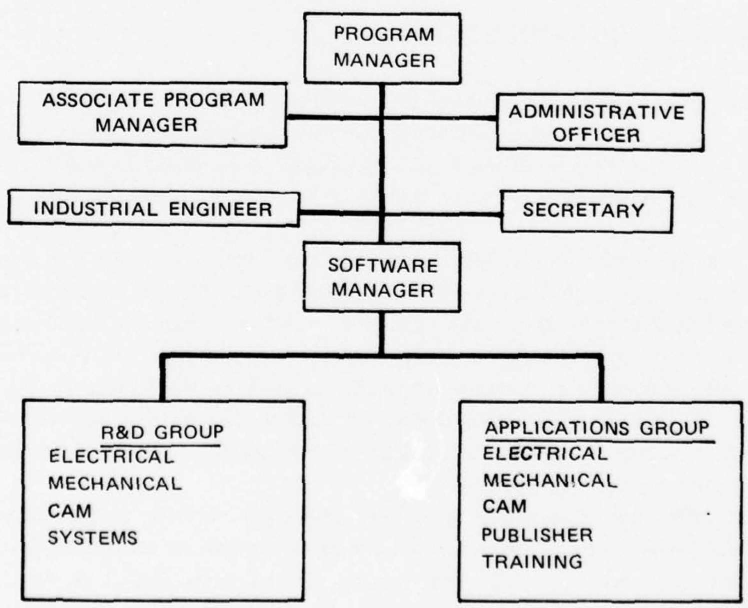



FIGURE 2. Proposed Support Organization.

The program manager would assume all coordination responsibility for the support organization. The associate program manager would assist in the coordination of the program, and also would be heavily involved in the national standards effort. The administrative officer's responsibility would be contract and productivity monitoring. The secretary would provide secretarial functions. The software manager would have complete control of the software groups and would also lead the NL MTIGS software committee. The industrial engineer will monitor NL system productivity.

The Software R&D Group's function would be to check out the system software, report the problems to the manufacturer, and develop solutions to the problems. The support organization would also provide a single point of contact for software problems for the NLs as well as the contractor. That would greatly simplify contractual problems. Each member would be involved with advanced planning in his/her particular area. One of the large payoffs of the future is analysis. The electrical and mechanical specialists would evaluate different approaches of linking analysis programs with MTIGS to shorten or improve the design cycle. The CAM specialist will be developing a viable N/C system. The system specialist would deal with NALCON, host interfaces, and appropriate linking of analysis programs.

The Applications Group would be primarily involved with developing, documenting, and training people in the use of application packages. The electrical, mechanical, and N/C specialists will develop the start files, macros, menus, and library components for each application and will implement the standards for each application package. The publisher would have the responsibility of developing standardized documentation for all the application packages. He/she also will coordinate the input of all system change requests. The training specialist, using vendor-supplied information and experience, will develop appropriate training materials for the basic system and application packages.

The support organization will contribute significantly to the increase of productivity for the NL MTIGS. It will also provide standardization of the application packages so that drawings can be passed easily from NL to NL without long, involved translation procedures.

## LOCAL LABORATORY ORGANIZATION

Each participating NL will have to determine for itself what kind of an organization it requires to support its MTIGS. The number of work stations to support and number of application packages being used will also help determine the size of the local organization. A proposed organization for the NWC Interactive Graphics Facility (IGF) is given in Figure 3 in order to present a typical large facility structure.

The facility manager's role would be to supervise the entire operation, find new customers, support the present ones, and plan for the future. The operations manager would be responsible for monitoring the contracts for maintenance and operation, interfacing with the Civil Service operators to see that their terminals are operating properly. The software manager will supervise all software development and will monitor any software contracts as well as participate in the NL MTIGS software committee. The present system programmer will support the existing Applicon MTIGS.

The Applications Group is expected to consist of five people. Their roles are very similar to their counterparts in the support organization.

Experience at NWC has shown that it is *very* important to have a standardized source of applications packages (Sandia Labs); however, these programs need to be tailored to local needs. This tailoring process does not take as much time as the development, but it is very important to increasing productivity. Therefore, the Applications Group will require three specialists: one each in electrical, mechanical, and system applications. They would tailor the packages to meet local needs.

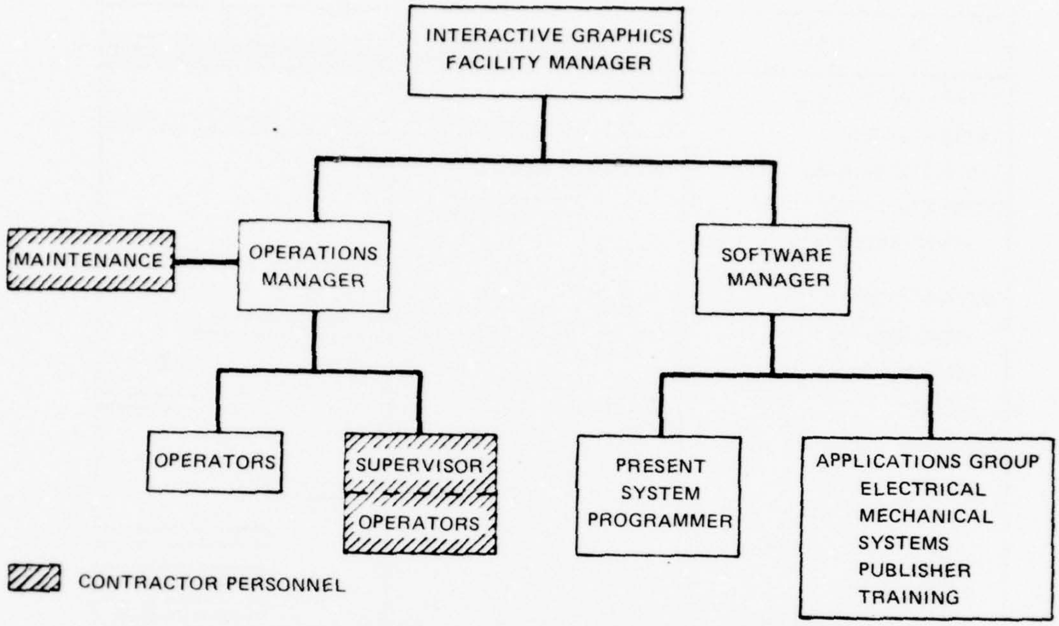



FIGURE 3. Proposed Naval Weapons Center Interactive Graphics Facility Organization.

The publisher properly documents the tailored packages and coordinates user requests to local and NL organizations. A monthly newsletter would also be published.

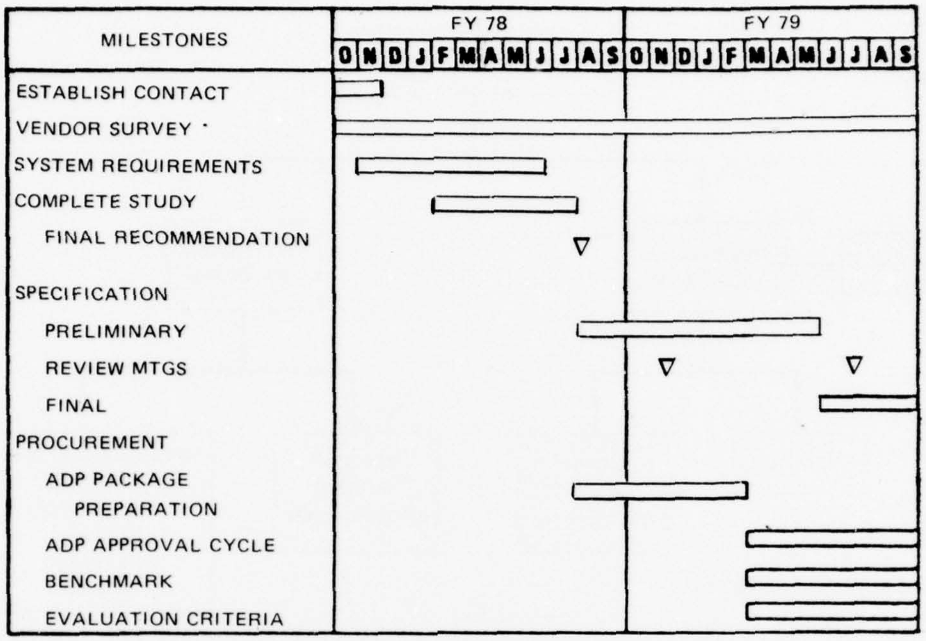
The training coordinator would train all operators and update them every 6 to 9 months. At major industrial installations, retraining has brought about significant productivity increases. New system features must be taught to the operators if they are to be used. Experience has taught that contracting out the operations manager position and key software positions significantly decreases effectiveness and productivity.

Although each NL needs to determine the size of its local MTIGS organization, it is suggested that at the least three billets, a facility manager, operations manager, and a software person, be provided. This will provide a good nucleus. In larger installations, more billets should be provided. More resources will increase the productivity and effectivity of the local MTIGS.

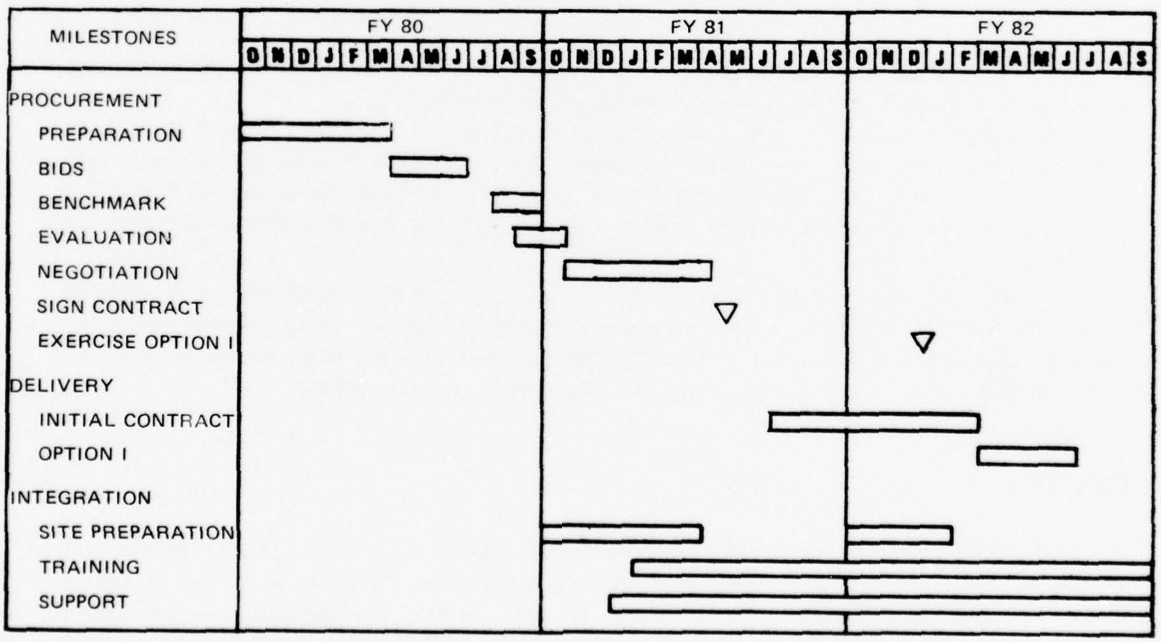
## FUNDING

The funding for the procurement can be spread over 2 or 3 years. Due to procurement restrictions, two-thirds of the funding must be obligated in the first phase or option. A second alternative would be to negotiate an indefinite delivery contract. The approval time for such a contract could be about 2 to 4 months more than for a stated quantity contract. There are also other contract administration problems associated with an indefinite delivery contract.

If funding is made available in FY 81 to procure an NL MTIGS, Figure 4 shows a realistic schedule to follow.




(a) FY 78-79 Milestones.




(b) FY 80, 81, 82 Milestones.

FIGURE 4. Proposed MTIGS Schedule.

## IMPLEMENTATION

Implementing interactive graphics at the NLs will not be a trivial process. Each installation will be only as successful as the level of support received from local top management and the efficiency of the local facility management. MTIGSs require top management support in the form of patience, billets, and space. (It will take 6 months for an MTIGS to start to become productive.) Sufficient space, with proper environmental control, is also necessary in order to have a successful facility. Approximately 600 square feet/central system and 150 square feet/terminal are recommended. Some of the larger installations will need more space for the central system because of the number of plotters required.

## STANDARDIZATION

MTIGSs exist presently at NOSC, NWC, and NSWC: two Computervision systems and one Applicon system. Many different vendors could be considered for the NL MTIGS contract award. However, none of the data bases of any of the vendors is compatible. This means that a drawing created on one system cannot be transferred to another. This problem of data base incompatibility is growing larger every day. It is similar to the problem that existed 15 to 20 years ago with the N/C machine tools before they were standardized. The MTIGS industry will not address the problem, because this would reduce each other's competitive edge; however, some industrial corporations are trying to develop their own standardized geometric data bases to help overcome this incompatibility problem. The U.S. Government is the logical agent to solve this problem, with help from industry. The National Bureau of Standards or the American National Standards Institute (ANSI) should be funded from all government agencies and tasked with finding solutions to this problem.

An important standard is being developed by ANSI committee Y14.26. This committee is defining the standard for passing geometric information between any two graphics data bases. The development of this standard will allow the passing of graphic data from the present Applicon and Computervision systems to the winning vendor of any future procurement. Navy support of the effort to attain public acceptance and the testing and writing of a translator incorporating the concepts of Y14.26 will be instrumental in the success of this first attempt at standardization.

## NALCON ROLE

NALCON is being developed in a joint effort by all the NLs. Transfer of data files from one NL to another will be possible under NALCON, and it would be the ideal way to transfer drawing files, new menus, and standardized parts libraries for MTIGS as well. This would facilitate communication among the NLs as well as provide a fast means of updating and exchanging information. This effort will be pursued.

## FUTURE

One of the most asked questions at the NL MTIGS briefings was whether this system can be used to facilitate analysis. At the present time, most vendors have developed preprocessors to construct

finite element grids, meshes and elements for stress analysis. At NWC, the IGF is considering development of a link between schematic diagrams and nonlinear circuit analysis programs. The capability of linking to analysis programs has tremendous potential and may be a very productive application in the future. Development of this analysis interface could be aided by the support organization's R&D group.

The MTIGS will be changing in other ways also; the hardware configurations in Table 6 show some expected changes. (It will probably take 2 to 3 years to see all these changes implemented.) The software will also be improving; it is expected that more verification and design aids will be made available. In the three-dimensional mechanical world, surface and solid capabilities will be added.

The impact of interactive graphics will no doubt continue to increase. Although the initial systems delivered to the NL will be starter systems, expanded growth should be expected shortly after the systems become productive. MTIGS is a dynamic, growing industry (see Figure 5). Hopefully, the NLs will support the MTIGS concept. This support will enable productivity increases in documentation, mechanical design, integrated circuit design, PCB design and fabrication, and N/C tape preparation. With continuing support, the MTIGS concept will become a powerful R&D tool at the NLs in the future.

TABLE 6. Present and Future System Configurations.

| | |
|---|---|
| Present system: | |
| Central system | |
| Minicomputer | 16 bit, 250K memory |
| Magnetic tape | 800/1600 bpi, 45 ips |
| Disk storage | 150 M, 16-bit words |
| Plotters | flatbed |
| Other peripherals | |
| Work stations - up to 4 | |
| Storage tube | 19 in. CRT |
| Future systems: | Distributed processing |
| Central system | |
| Minicomputer | 32 bit, 2 M words memory |
| Magnetic tape | 1600/6250 bpi, 125 ips |
| Disk storage | 250 M, 32-bit words |
| Plotters | ink jet |
| Other peripherals | |
| Work stations - up to 8 | |
| Raster scan video | 25" CRT |
| Microprocessor | 100K words memory |
| Local storage | Floppy discs |

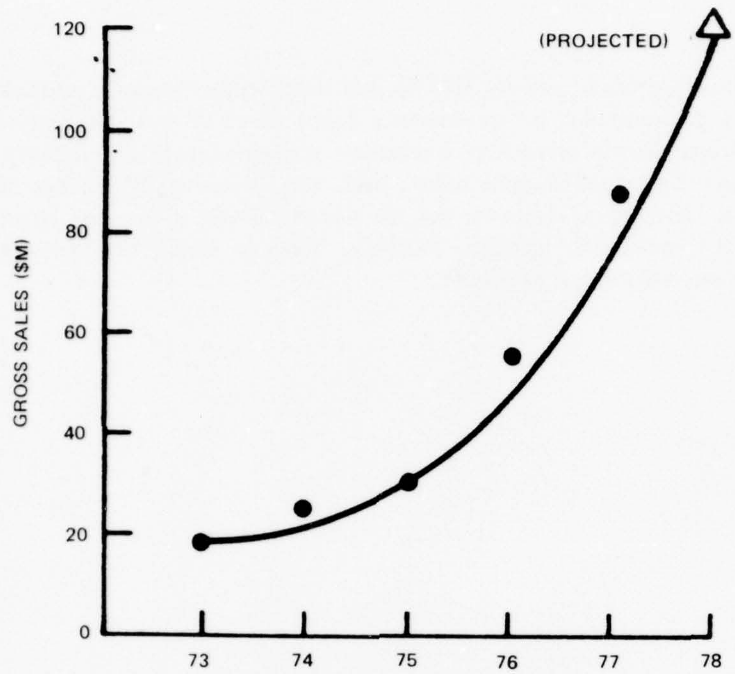



FIGURE 5. MTIGSs Gross Sales.

## SUMMARY

### RECOMMENDATIONS

As a result of this study, the following recommendations are made:

1. That DLP make $10M in funding available for a competitive procurement for an MTIGS for the NLs.
2. That a support organization be designated for MTIGS.
3. That a productive study be initiated at NWC to determine methods of monitoring interactive graphics system productivity.
4. That each NL participating in the procurement submit an implementation plan (including billets and space) to NAVMAT.
5. That the Navy identify funds to support the public acceptance, testing and translator development of the ANSI Y14.26; that a continued effort be made to solicit funds to support this standard from other DOD agencies.

## CONCLUSION

The NLs have a legitimate need for MTIGSs, and the procurement cost is justified. The ability to handle design and documentation information in a digital data base is a state-of-the-art technology. Developing and maintaining this technology is necessary in staying current with industry and the future methods of product design and documentation. Also, with decreasing NL ceilings the NLs have a definite interest in increasing productivity, and the use of MTIGSs is one very effective method of accomplishing that productivity increase. Therefore, funding should be identified so that the procurement cycle can start as soon as possible.

## NOMENCLATURE

| | |
|---|---|
| ANSI | American National Standards Institute |
| APT | Automatic Program Tools |
| CAD | Computer Aided Design |
| CAD/CAM | Computer Aided Design/Computer Aided Manufacturing |
| CAM | Computer Aided Manufacturing |
| CLTAPE | Center Line Tape |
| COM | Computer Output Microfilm |
| DL | NSWC located at Dahlgren, VA |
| DLP | Director of Laboratory Programs |
| ECP | Engineering Change Proposal |
| IC | Integrated Circuit |
| IGF | Interactive Graphics Facility |
| LAD | Layout and Arrangement Drawing |
| MTIGS | Minicomputer Turnkey Interactive Graphics System |
| NADC | Naval Air Development Center, Warminster, PA |
| NALCON | Navy Laboratory Computer Network |
| N/C | Numerical Control |
| NCSC | Naval Coastal System Center, Panama City, FL |
| NL | Navy Laboratory |
| NLN | NUSC located at New London, CT |
| NLCC | Navy Laboratory Computer Committee |
| NLIGS | Navy Laboratory Interactive Graphics Study |
| NOR | Notice of Revision |
| NOSC | Naval Ocean Systems Center, San Diego, CA |
| NPT | NUSC located at Newport, RI |
| NSRDC | Naval Ship Research and Development Center, Bethesda, MD |
| NSWC | Naval Surface Weapons Center, Dahlgren, VA |
| NUSC | Naval Underwater Systems Center, Newport, RI |
| NWC | Naval Weapons Center, China Lake, CA |
| PCB | Printed Circuit Board |
| R&D | Research and Development |
| SO | Support Organization |
| TOL | Tolerance Study |
| VLSI | Very Large Scale Integration |
| WO | NSWC located at White Oak, MD |

# Appendix A
# ORIGINAL AND UPDATED FUNDING PROPOSALS

DEPARTMENT OF THE NAVY
HEADQUARTERS NAVAL MATERIAL COMMAND
WASHINGTON, D. C. 20360

IN REPLY REFER TO
08T1/TAK
Ser 385

24 AUG 1977

From: Chief of Naval Material
To: Commander, Naval Weapons Center

Subj: Investigation of Interactive Graphic Needs of Navy Laboratories

Ref: (a) NWC DD Form 1498 Study Proposal

1. The rising interest of the CNM laboratories in interactive graphic system acquisitions and the wide application of these systems within the laboratory environment indicate a need for a closer examination of these systems with the aim to standardize on a laboratory system or systems which can possibly be networked among the laboratories. The subject investigation, proposed by reference (a), is approved up through specification preparation and will be funded by NAVMAT (MAT 08T1) in Fiscal Year 1978.

2. The conduct of the investigation should be coordinated with the Navy Laboratory Computer Committee to assure compatibility of existing computational systems and any interactive graphic system that may be proposed and/or presently exists. The future acquisition of a "laboratory interactive graphic networked system", will be dependent on the study recommendations and the success in defending future budget requests for the system acquisition. The increased productivity made possible with an interactive graphic system makes it a likely candidate for the fast-payback program if the current dollar thresholds are raised - a decision presently under consideration.

3. In addition to the NWC system, NSWC/WO has an interactive graphics system under procurement. Until completion of subject investigation, no further similar procurements will be approved by NAVMAT.

James H. Probus

JAMES H. PROBUS
By direction

Copy to:
NLCC (G. Gleissner) (w/cy of ref (a))
NAVAIRDEVCEN
NAVCOASTSYSLAB
DTNSRDC
NAVOCEANSYSCEN
NAVPERSRANDCEN
NAVSURFWPNCEN
NUSC NPT

**RESEARCH AND TECHNOLOGY WORK UNIT SUMMARY**

| 10. NO./CODES | PROGRAM ELEMENT | PROJECT NUMBER | TASK AREA NUMBER | WORK UNIT NUMBER |
|---|---|---|---|---|
| a. PRIMARY | | | | |
| b. CONTRIBUTING | | | | |
| c. CONTRIBUTING | | | | |

11. TITLE (Precede with Security Classification Code)

(U) Study of Present and Future Interactive Graphics Needs at Navy Laboratories

12. SCIENTIFIC AND TECHNOLOGICAL AREAS

13. START DATE: OCT 1977

14. ESTIMATED COMPLETION DATE: SEP 1980

15. FUNDING AGENCY

16. PERFORMANCE METHOD

17. CONTRACT/GRANT

a. DATES/EFFECTIVE: EXPIRATION:

b. NUMBER:

c. TYPE: d. AMOUNT:

e. KIND OF AWARD: f. CUM TOTAL:

18. RESOURCES ESTIMATE

| FISCAL YEAR | a. PROFESSIONAL MAN YEARS | b. FUNDS (In thousands) |
|---|---|---|
| PRECEDING | | |
| CURRENT | | |

19. RESPONSIBLE DOD ORGANIZATION

NAME: Navy Laboratories

ADDRESS: Washington, DC

RESPONSIBLE INDIVIDUAL

NAME: Mr. James H. Probus

TELEPHONE:

20. PERFORMING ORGANIZATION

NAME: Naval Weapons Center

ADDRESS: China Lake, CA 93555

PRINCIPAL INVESTIGATOR (Furnish SSAN if U.S. Academic Institution)

NAME: Dale O. Christensen

TELEPHONE: (714) 939-3364

SOCIAL SECURITY ACCOUNT NUMBER:

ASSOCIATE INVESTIGATORS

NAME: John E. Anderson

NAME:

21. GENERAL USE

22. KEYWORDS (Precede EACH with Security Classification Code)

23. TECHNICAL OBJECTIVE, 24. APPROACH, 25. PROGRESS (Furnish individual paragraphs identified by number. Precede text of each with Security Classification Code.)

23. (U) The technical objective of this program is to define the present and future needs of all Navy Laboratories in the area of interactive graphics, to establish representatives at each Navy Laboratory as a key contact, to make a recommendation to the Director of Navy Laboratories as to whether it is feasible to develop a independent network of interactive graphics facility within the Navy Laboratory system, and if feasible, to write a purchase specification, and to procure the system.

24. (U) Each Navy Laboratory will be visited, their mission reviewed, and possible areas defined where the use of interactive graphics would increase productivity and reduce costs. With this information, the feasibility of a networked interactive graphics system will be evaluated.

25. (U) Nothing is presently being done in this area.

*Available to contractors upon originator's approval.

DD FORM 1498

LABORATORY PROGRAM SUMMARY
11ND-NWC-3910 49 (REV. 12-74)

CLASSIFICATION AND DOWNGRADING GROUP

| | | |
|---|---|---|
| | ACTIVITY: NAVAL WEAPONS CENTER | WORK UNIT NUMBER |
| 27. TECHNICAL AGENT | 26. PRIOR IDENTIFICATION | |

| 28. MANPOWER AND COST ESTIMATES | FY 7 CFY-1 | FY 7 CFY | FY 7 CFY+1 | FY 7 CFY+2 | FY 7 CFY+3 |
|---|---|---|---|---|---|
| A. PROFESSIONAL MAN-YEARS | | | 1.5 | 1.5 | 1.0 |
| B. TOTAL DIRECT LABOR MAN-YEARS | | | 1.5 | 1.5 | 1.0 |
| C. TOTAL LABOR AND OVERHEAD ($ K) | | | 100 | 110 | 80 |
| D. MATERIALS AND TRAVEL ($ K) | | | 25 | 15 | 25 |
| E. MAJOR PROCUREMENTS CONTRACTS ($ K) | | | | 8000 | |
| F. PLANNING ESTIMATE ($ K) | | | 125 | 8125 | 105 |
| G. FUNDS AVAILABLE ($ K) | | | 0 | 0 | 0 |
| H. | | | | | |
| H. | | | | | |

29. BACKGROUND 30. PLANS AND MILESTONES 31. REFERENCES 32. MAJOR PROCUREMENTS AND CONTRACTS. 33. SPECIAL REQUIREMENTS (*Furnish individual paragraphs, precede each with Security Classification Code*).

29. (U) Presently, there are over 500 mini-computer based interactive graphics systems in business and industry in the United States. Interactive graphics does reduce costs, increase productivity, and save time. Productivity increases of 5:1 are common in industry. Interactive graphics is an aid and can be utilized for design, drafting, documentation, and analysis. The NAVWPNCEN procured its interactive graphics system in FY 76 and FY 7TQ, and received it in December 1976. Since then the system has been utilized by many people. It has been and is being learned first hand where the problems and key concerns are.

30. (U) Milestones

| | | |
|---|---|---|
| a. | Establish contact person at each Navy Laboratory | 15 NOV 77 |
| b. | Define system requirements for each Navy Laboratory | 01 FEB 78 |
| c. | Conduct a market survey of interactive graphics vendors | 01 FEB 78 |
| d. | Complete study | 01 MAY 78 |
| e. | Write a system specification | 01 SEP 78 |
| f. | Prepare RFP | 01 DEC 78 |
| g. | Prepare benchmark | 01 DEC 78 |
| h. | Evaluate responses | 01 APR 79 |
| i. | Sign contract | 01 JUL 79 |
| j. | Followup at site installations | 01 OCT 80 |

| APPROVED | DEPARTMENT | DIVISION | PROJECT MANAGER | CODE | PHONE |
|---|---|---|---|---|---|
| DATE | | | | PAGE OF | |

CLASSIFICATION

**LABORATORY PROGRAM SUMMARY/NARDIS REPORT (CONT. SHEET)**
11ND-NWC-3910/50 (REV. 6-71)

CLASSIFICATION

| WORK UNIT NO. | ACTIVITY |
|---|---|
| | NAVAL WEAPONS CENTER |

32. (U) The major procurement would be the purchase of a networked interactive graphics system at the cost of approximately $8,000,000.00.

| DATE | PAGE |
|---|---|
| | OF |

CLASSIFICATION

[redacted]

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FROM COPY FURNISHED TO DDC



UNCLASSIFIED

| RESEARCH AND TECHNOLOGY WORK UNIT SUMMARY | | | | 1. AGENCY ACCESSION* | | 2. DATE OF SUMMARY* | REPORT CONTROL SYMBOL |
|---|---|---|---|---|---|---|---|
| | | | | DN882016 | | 790226 | |
| 3. DATE OF PREV SUM'RY | 4. KIND OF SUMMARY | 5. SUMMARY SCTY* | 6. WORK SECURITY* | 7. REGRADING* | 8a. DISB'N INSTR'N | 8b. SPECIFIC DATA CONTRACTOR ACCESS | 9. LEVEL OF SUM |
| 790207 | D. CHANGE | U | U | | GU | [X] YES [ ] NO | A. WORK UNIT |

| 10. NO/CODES:* | PROGRAM ELEMENT | PROJECT NUMBER | TASK AREA NUMBER | WORK UNIT NUMBER |
|---|---|---|---|---|
| A. PRIMARY | 65861N | Z0832-SL | Z0832-SL | 133060 |
| B. CONTRIBUTING | 65862N | Z0833-SL | Z0833-SL | |
| C. CONTRIBUTING | 35 | MISSION SUPPORT | | |

11. TITLE (Precede with Security Classification Code): (U)NL INTERACTIVE GRAPHICS PROGRAM

12. SCIENTIFIC AND TECHNOLOGICAL AREAS* 004200 COMPUTERS
005700 ELECTRON ELECT ENG 009200 MACHINERY, TOOLS

| 13. START DATE | 14. ESTIMATED COMPLETION DATE | 15. FUNDING AGENCY | 16. PERFORMANCE METHOD |
|---|---|---|---|
| 771003 | 810930 | DN | C. IN-HOUSE |

17. CONTRACT/GRANT
A. DATES/EFFECTIVE: EXPIRATION:
B. NUMBER:*
C. TYPE* D. AMOUNT:
E. KIND OF AWARD: F. CUM TOTAL:

| 18. RESOURCES ESTIMATE | | A. PROFESSIONAL MAN YEARS | B. FUNDS (In thousands) |
|---|---|---|---|
| FISCAL YEAR | PRECEDING 78 | 1.3 | 157 |
| | CURRENT 79 | 1.7 | 350 |

19. RESPONSIBLE DOD ORGANIZATION 402568
NAME:* NAVAL MATERIAL COMMAND
ADDRESS:* WASHINGTON, D.C. 20376
RESPONSIBLE INDIVIDUAL
NAME: KLEBACK, T. 08T121
TELEPHONE: 202-692-3426

20. PERFORMING ORGANIZATION 403019
NAME:* NAVAL WEAPONS CENTER
ADDRESS:* CHINA LAKE, CALIF. 93555
PRINCIPAL INVESTIGATOR (Furnish SSAN if U.S. Academic Institution)
NAME:* CHRISTENSEN, D.O. 3306
TELEPHONE: 714-939-3010
SOCIAL SECURITY ACCOUNT NUMBER:
ASSOCIATE INVESTIGATORS
NAME: ANDERSON, J.E.
NAME:

21. GENERAL USE
C

22. KEYWORDS (Precede EACH with Security Classification Code) (U)INTERACTIVE GRAPHICS

23. TECHNICAL OBJECTIVE.* 24. APPROACH. 25. PROGRESS (Furnish individual paragraphs identified by number, precede text of each with security classification code.)

23. (U) TECHNICAL OBJECTIVE: THE TECHNICAL OBJECTIVE OF THE NAVY LABORATORY INTERACTIVE GRAPHICS PROGRAM IS TO PROCURE AND INSTALL A MINI COMPUTER TURNKEY INTERACTIVE GRAPHICS SYSTEM IN EACH OF THE NAVY LABORATORIES IN FY 80-81. THIS SYSTEM IS TO INCREASE MANPOWER PRODUCTIVITY AND REDUCE THE COST OF DOCUMENTATION.

24. (U) APPROACH: THE MTIGS WILL BE PROCURED OVER A TWO-YEAR PERIOD IN FY81-82. THE DETAIL SYSTEM SPECIFICATION AND OTHER ADP APPROVAL DOCUMENTS WILL BE WRITTEN AND SUBMITTED IN MARCH 1979. THE BENCH MARK AND PROCUREMENT EVALUATION PACKAGE WILL ALSO BE PREPARED IN FY 79. FINAL VERSION OF THE SPECIFICATION WILL BE COMPLETED IN LATE FY 79.

25. (U) PROGRESS: (OCTOBER 1977 - SEPTEMBER 1978) EACH NAVY LABORATORY WAS VISITED AND INTERACTIVE GRAPHICS APPLICATION AREAS WERE DEFINED. EACH LABORATORY SUBMITTED ITS REQUIREMENTS FOR COMPILATION INTO A NAVY LABORATORY REPORT. THE REPORT IS IN THE FINAL APPROVAL CHAIN AND WILL BE ISSUED IN EARLY FY 79. PREPARATION OF THE SPECIFICATION HAS STARTED.

*Available to contractors upon originator's approval.



[redacted]

LABORATORY PROGRAM SUMMARY
11ND-NWC-3910/49 (REV. 12-74)

CLASSIFICATION AND DOWNGRADING GROUP
UNCLASSIFIED

| | ACTIVITY | WORK UNIT NUMBER |
|---|---|---|
| | NAVAL WEAPONS CENTER | 133060 |
| 27. TECHNICAL AGENT | 26. PRIOR IDENTIFICATION | |

| 28. MANPOWER AND COST ESTIMATES | FY 78 CFY-1 | FY 79 CFY | FY 80 CFY+1 | FY 81 CFY+2 | FY 82 CFY+3 |
|---|---|---|---|---|---|
| A. PROFESSIONAL MAN-YEARS | 1.3 | 1.7 | 5.0 | 12.0 | 12.0 |
| B. TOTAL DIRECT LABOR MAN-YEARS | 1.5 | 2.2 | 6.0 | 13.0 | 13.0 |
| C. TOTAL LABOR AND OVERHEAD ($K) | 96 | 162 | 371 | 870 | 870 |
| D. MATERIALS AND TRAVEL ($K) | 28 | 43 | 369 | 130 | 130 |
| E. MAJOR PROCUREMENTS/CONTRACTS ($K) | 33 | 145 | 270 | 7000 | 3600 |
| F. PLANNING ESTIMATE ($K) | | 350 | 1010 | 8000 | 4600 |
| G. FUNDS AVAILABLE ($K) | 160 | 350 | 0 | 0 | 0 |
| H. | | | | | |
| H. | | | | | |

29. BACKGROUND 30. PLANS AND MILESTONES 31. REFERENCES 32. MAJOR PROCUREMENTS AND CONTRACTS 33. SPECIAL REQUIREMENTS (Furnish individual paragraphs. Precede each with Security Classification Code).

29. (U) BACKGROUND: THE NAVY LABORATORY INTERACTIVE GRAPHICS STUDY WAS INITIATED IN FY 78. THE RESULTS OF THAT STUDY SHOWED THAT THERE IS A LEGITIMATE AND COST JUSTIFIABLE NEED FOR MINI COMPUTER TURNKEY INTERACTIVE GRAPHICS SYSTEMS (MTIGS) IN THE NAVY LABORATORIES. BASED ON THE RESULTS OF THE STUDY, FUNDING HAS BEEN IDENTIFIED TO PROCURE A MTIGS FOR ALL CNM R+D LABS.

| 30. PLANS AND MILESTONES | | START | COMP |
|---|---|---|---|
| FY 1979. | | | |
| PLANS | (U)PREPARE RFP FOR NETWORKED INTERACTIVE GRAPHICS SYSTEM. PREPARE BENCHMARK AND EVALUATE RESPONSES TO RFP. SECURE ADP APPROVAL. STUDY PRODUCTIVITY DETERMINATION TECHNIQUES. | | |
| MILESTONES | (U)COMPLETED ADP APPROVAL PACKAGE | 7806 | 7903 |
| | (U)PREPARE BENCHMARK | 7901 | 7911 |
| | (U)PREPARE EVALUATION CRITERIA | 7901 | 7911 |
| | (U)COMPLETE FINAL SYSTEM SPECIFICATION | 7810 | 7911 |
| | (U)COMPLETE ADP APPROVAL CYCLE | 7901 | 7910 |
| FY 1980. | | | |
| PLANS | (U)START PROCUREMENT OF MTIGS TEACH PEOPLE IN USE AND MANAGEMENT OF SYSTEM. | | |
| MILESTONES | (U)RFP ON STREET | 8003 | 8006 |
| | (U)BENCHMARK | 8007 | 8009 |
| | (U)EVALUATION | 8008 | 8010 |
| FY 1981. | | | |
| MILESTONES | (U)NEGOTIATION | 8012 | 8103 |
| | (U)SIGN CONTRACT | 8104 | 8104 |
| | (U)SUPPORT ORGANIZATION | 8010 | 8105 |
| | (U)HARDWARE DELIVERY | 8105 | 8202 |
| FY 1982. | | | |
| MILESTONES | (U)EXERCISE OPTION FOR ADDITIONAL HARDWARE | 8101 | 8101 |

DATE 790226

PAGE 2 OF 3

CLASSIFICATION UNCLASSIFIED

LABORATORY PROGRAM SUMMARY (CONT. SHEET) CLASSIFICATION UNCLASSIFIED
11ND-NWC-3910/50 (REV. 12-74)

WORK UNIT NUMBER 133060 | ACTIVITY NAVAL WEAPONS CENTER

30. CONT'D
(U)OPTION 1 HARDWARE DELIVERY 8103 8107

31. REFERENCES
(U)NONE

32. MAJOR PROCUREMENTS AND CONTRACTS

| | ITEM | LET-DATE | $SERV | $MAT'L | DEL-DATE | CONTRACTOR |
|---|---|---|---|---|---|---|
| FY 1979. | (U)INTERACTIVE GRAPHICS SUPPOR | 7901 | 145 | | 7909 | |
| FY 1980. | (U)INTERACTIVE GRAPHIC SUPPORT | 7910 | 250 | | 8009 | TBD |
| | (U)INTERACTIVE GRAPHIC EQUIPME | 8001 | | 250 | 8006 | APPLICON |
| FY 1981. | (U)NETWORKED INTERACTIVE GRAPH | 8104 | 3300 | 6700 | 8107 | TBD |
| | (U)INTERACTIVE GRAPHICS SUPPOR | | 300 | | | TBD |
| FY 1982. | (U)NETWORKED INTERACTIVE GRAPH | 8112 | | 3300 | 8202 | TBD |
| | (U)INTERACTIVE GRAPHICS SUPPOR | | 300 | | | TBD |

33. SPECIAL REQUIREMENTS
FACILITY DATE REQ
(U)NONE
SKILL DATE REQ
(U)NONE
AIRCRAFT TYP MODIFICATION FLT HRS REQ
(U)NONE
EQUIPMENT DATE REQ
(U)NONE

DATE 790226 | PAGE 3 OF 3

CLASSIFICATION UNCLASSIFIED

## Appendix B

## COST JUSTIFICATION ASSUMPTIONS

For the MTIGSs, the issues of cost savings and productivity increases are complex. Many factors are difficult to measure either by direct cost or time savings.

All NL contact points agreed that the dollar savings reported should be quantifiable savings. To comply with this assumption, measurable savings had to be defined. It was agreed that a comparable quality criterion would be used: the cost to produce a drawing *manually* would be compared directly to the cost to produce an *automated* drawing of similar quality.

Some of the intangible savings that are very difficult to measure in dollars are not included in the real-dollar savings. For instance, the design sophistication level of today's weapons is increasing rapidly. The cost of manually producing these designs is becoming so high that automated techniques must be used in some instances. Therefore, MTIGS would be used to complete these designs in any case.

Time savings are beneficial and allow for other benefits. If it takes only half as long to design a weapon system or subsystem on the MTIGS, more time can be spent in perfecting the design in the design phase. It is difficult to measure that savings in real dollars. Also, MTIGSs allow the designers to have capabilities such as rotation and translation of parts available for tolerance studies in minutes instead of weeks. The result is a far superior and more timely initial design, but it is almost impossible to quantify the real-dollar savings resulting from a superior initial design.

A 5-year system life was assumed. This system life is typically used in industry.

A productivity increase of 2:1 or 2.6:1 for all application areas (comparable quality being assumed) over the system life was estimated. Many productivity ratios have been published in the open literature. The NWC interactive graphics facility has shown productivity ratios of 2:1 to 4:1 for the preparation of electrical documentation. Industrial users show productivity ratios of 3:1 to 4:1 for the preparation of PC boards. The mechanical design productivity ratios are lower; most range from 1.5:1 to 2:1. However, when tailored to specific applications, a large automotive manufacturer has consistently measured productivity ratios of 4:1 to 5:1 for tool and machine design. Thus, the productivity ratio of 2:1 or 2.6:1 appears to be a conservative estimate over the life of the system.

MTIGSs do not start on the first day at a 2:1 productivity ratio. It takes approximately 1 to 4 months in electrical applications and 3 to 8 months in mechanical applications to train users and arrive at a productivity ratio of 1:1. However, by the end of the first year, the productivity ratios should be approaching 2:1. This increases slightly during the second year and then levels off. Thus, at least 6 months are necessary to allow an MTIGS to become productive.

The cost of MTIGS was assumed to be approximately \$100K per work station. This was a very conservative estimate which included the central system with all the necessary peripherals. A work station includes a display with a hard copy unit where a technician or engineer can manipulate graphics data.

The work load of each NL in the MTIGS applications areas was assumed to be constant over the system life. In reality, it will probably increase.

The cost savings were summarized on Attachment 1 of NAVCOMPINST 7000.38 dated August 1977. This is the standard fast-payback format for the report.

# Appendix C
# NLIGS APPLICATION AREAS

The application areas for MTIGS are growing rapidly. The five NLIGS application areas at present are documentation; mechanical design and layout; integrated circuit design; PCB design, layout, and manufacture; and tape preparation for N/C machine tools.

## DOCUMENTATION

Documentation is a product of every NL. Everything that is designed, built, or under contract to be designed or built must be documented. Piece-part drawings and schematics must be created. With MTIGS, piece parts can be dimensioned quickly and notes added to complete the drawing. Then assembly drawings can be created directly from the piece part drawings. This is a very cost-effective way to generate assembly drawings. Notices of Revision (NORs) and Engineering Change Proposals (ECPs) can be incorporated into the drawings very quickly, since they already reside in the data base. Assembly drawings can then be quickly updated if necessary.

## MECHANICAL DESIGN/LAYOUT

Design layouts can be performed on the computer much faster and better than using conventional drafting techniques. In addition, with the designed parts stored in the computer, these parts can be manipulated (rotated, translated, etc.) much faster than by conventional techniques. Many more design iterations can be completed. When the layout is complete, the piece-part geometry already created can be used to create the piece-part and assembly drawings, saving time and money in drawing preparation.

## INTEGRATED CIRCUIT DESIGN (IC)

Integrated circuit design at the present complexity levels requires a computer-aided design (CAD) system. The decrease in physical size and increase in numbers of components in very large scale integration (VLSI) designs require a sophisticated graphics system to keep track of and properly manipulate the design. Once the components are entered into the system, verification aids are used to test for component interference and clearances. Then an N/C tape can be generated to create an IC mask.

## PCB DESIGN

The designing of PCBs was one of the first application areas of MTIGS. Block diagrams, schematics, and logic diagrams are created easily on the MTIGS. Once the schematic is complete, aids are available to help properly place the components on the board.

Routing programs are also available to assist the operator route the board. These routers run on a minicomputer and are not very sophisticated, but they do eliminate much of the tedium of the routing process.

When the routing process is complete, a number of verification aids are available. A program will check the schematic and the layout to verify that the connections are the same. Another program will verify that proper clearances have been maintained between all the solder runs and components. A net list capability is available to check electrical connections, even over multiple drawing sheets. A bill of materials listing can also be automatically generated.

After the PCB has been properly verified, the manufacturing process can begin. A photoplotter output tape can be generated directly from the layout stored in the data base. This allows the creation of a photoplot which can be used directly as an etching master. An N/C drill tape can also be automatically generated. With this tape, a PCB can be automatically drilled. Output tapes for automatic wire wrap machines or component insertion machines can also be generated. This PCB package will bring a very powerful tool to the NLs.

## N/C MACHINE TAPE PREPARATION

The capability exists within the MTIGS to create three-dimensional geometries. Once this geometry has been generated, tool paths which simulate the machining process can be generated. Milling and drilling presently can be accommodated. The N/C part programmer can check and edit any errors in the program before actually machining the part. The MTIGS will then create an automatic program tools source program or a centerline tape which can be input to a standard automatic program tools system for processing. Then the part can be machined on an N/C machine.

These five application areas have great potential at the NLs. The MTIGSs should help the laboratory community do its job faster, easier, cheaper, and better.

## Appendix D
## DETAILED CALCULATIONS OF SEVEN ALTERNATIVE PLANS

### SUBMITTED PLAN

Each NL submitted a cost analysis for implementing an interactive graphics system at its site. This cost analysis was based on the agreed-upon assumptions (see Appendix C). Each NL handled the computations a bit differently. These cost analyses are summarized in Plan 4.

### ALTERNATIVE PLANS

At the request of the DLP's staff, different funding levels were evaluated. Additional assumptions were made so that a fair evaluation could be conducted.

The number of requested work stations far surpassed the original program estimates. If fewer work stations were to be provided, all calculations had to be adjusted. The man-year labor rates were calculated for each NL based on the submitted information. Each NL's labor rate was used throughout all the calculations. Each NL also had different utilization factors, which varied from 0.94 to 1.76 man-year/work station. An assumption was made that 1.0 man-year/work station was most conservative. It is also assumed that there would be enough work to fill the work station for 1.0 man-year. Based on the experience of NWC and NSWC/WO, both assumptions are very conservative. Using these assumptions, the manual and CAD labor costs were calculated.

The CAD indirect labor costs (based upon each NL's labor rate) were assumed to be constant and not plan dependent. This is reasonable, since a basic level of support is necessary. A minimum of 3 man-years/year for each Navy laboratory was assumed. A maintenance cost of $10K/work station/year was assumed, based on MTIGS industry estimates. The other manual costs, CAD material costs, and CAD other costs were prorated on the number of work stations being supplied. Constant FY 78 dollars were used, and a 5-year system life was assumed. Plans 5, 6, and 7 were derived using the above assumptions with a productivity increase of 2.0:1.

After extensive discussions with leading industrial users and based on the experience at NWC and NSWC, it is apparent that MTIGSs require a support organization in order to realize the largest productivity gains. Plans 1, 2, and 3 are based on the same assumptions as Plans 5, 6, and 7 except a productivity of 2.6:1 was assumed as a result of the inclusion of a support organization.

The details of each plan for each NL are given in the following pages.

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 1
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 8 | 104 | 5,146 | 24 | 5,170 | 40 | 1,979 | 32 | 780 | 400 | 0 | 3,191 | 1,979 |
| NCSC | 5 | 65 | 1,884 | 73 | 1,957 | 25 | 725 | 20 | 406 | 250 | 0 | 1,401 | 556 |
| NOSC | 10 | 130 | 4,204 | 20 | 4,224 | 50 | 1,617 | 40 | 485 | 500 | 50 | 2,692 | 1,532 |
| NSRDC | 10 | 130 | 6,500 | 30 | 6,530 | 50 | 2,500 | 50 | 700 | 500 | 0 | 3,750 | 2,780 |
| NSWC | | | | | | | | | | | | | |
| DL | 9 | 117 | 5,039 | 30 | 5,069 | 45 | 1,938 | 30 | 646 | 450 | 20 | 3,084 | 1,985 |
| WO | 5 | 65 | 2,826 | 25 | 2,851 | 25 | 1,087 | 20 | 653 | 250 | 18 | 2,028 | 823 |
| NUSC | | | | | | | | | | | | | |
| NPT | 17 | 221 | 10,166 | 38 | 10,204 | 85 | 3,910 | 77 | 541 | 850 | 0 | 5,378 | 4,826 |
| NLN | 22 | 286 | 13,174 | 67 | 13,241 | 110 | 5,067 | 100 | 700 | 1,100 | 0 | 6,967 | 6,274 |
| NWC | 24 | 312 | 20,523 | 48 | 20,571 | 120 | 7,894 | 96 | 821 | 1,200 | 0 | 10,011 | 10,561 |
| SO | 5 | | | | | | | 750 | 4,000 | 250 | 0 | 5,000 | (5,000) |
| TOTALS | 115 | 1,430 | 69,464 | 355 | 69,819 | 550 | 26,717 | 1,215 | 9,732 | 5,750 | 88 | 43,502 | 26,317 |

Assumptions:

- *Support organization*
- 2.6:1 productivity increase
- 5-year system life
- Constant FY 78 dollars
- One man-year/work station
- Enough work
- Maintenance cost $10K/work station/year
- Constant support cost

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 2
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 7 | 91 | 4,503 | 21 | 4,524 | 35 | 1,732 | 28 | 780 | 350 | 0 | 2,890 | 1,634 |
| NCSC | 4 | 52 | 1,507 | 58 | 1,566 | 20 | 580 | 16 | 406 | 200 | 0 | 1,202 | 364 |
| NOSC | 9 | 117 | 3,784 | 18 | 3,802 | 45 | 1,455 | 36 | 485 | 450 | 45 | 2,471 | 1,331 |
| NSRDC | 9 | 117 | 5,850 | 26 | 5,876 | 45 | 2,250 | 43 | 700 | 450 | 0 | 3,443 | 2,433 |
| NSWC | | | | | | | | | | | | | |
| DL | 8 | 104 | 4,479 | 27 | 4,506 | 40 | 1,723 | 27 | 646 | 400 | 18 | 2,813 | 1,693 |
| WO | 4 | 52 | 2,261 | 20 | 2,281 | 20 | 870 | 16 | 653 | 200 | 14 | 1,753 | 528 |
| NUSC | | | | | | | | | | | | | |
| NPT | 15 | 195 | 8,970 | 34 | 9,004 | 75 | 3,450 | 68 | 541 | 750 | 0 | 4,809 | 4,195 |
| NLN | 18 | 234 | 10,779 | 55 | 10,834 | 90 | 4,146 | 82 | 700 | 900 | 0 | 5,828 | 5,006 |
| NWC | 18 | 234 | 15,392 | 36 | 15,428 | 90 | 5,920 | 72 | 821 | 900 | 0 | 7,713 | 7,715 |
| SO | 5 | | | | | | | 750 | 4,000 | 250 | 0 | 5,000 | (5,000) |
| TOTALS | 97 | 1,196 | 57,526 | 294 | 57,820 | 460 | 22,125 | 1,137 | 9,732 | 4,850 | 77 | 37,921 | 19,898 |

Assumptions:

| | |
|---|---|
| Support organization | One man-year/work station |
| 2.6:1 productivity increase | Enough work |
| 5-year system life | Maintenance cost $10K/work station/year |
| Constant FY 78 dollars | Constant support cost |

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 3
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 4 | 52 | 2,573 | 12 | 2,585 | 20 | 990 | 16 | 780 | 200 | 0 | 1,986 | 600 |
| NCSC | 3 | 39 | 1,130 | 44 | 1,174 | 15 | 435 | 12 | 406 | 150 | 0 | 1,003 | 171 |
| NOSC | 5 | 65 | 2,102 | 10 | 2,112 | 25 | 809 | 20 | 485 | 250 | 25 | 1,589 | 524 |
| NSRDC | 5 | 65 | 3,250 | 15 | 3,265 | 25 | 1,250 | 25 | 700 | 250 | 0 | 2,225 | 1,040 |
| NSWC | | | | | | | | | | | | | |
| DL | 5 | 65 | 2,800 | 17 | 2,816 | 25 | 1,077 | 17 | 646 | 250 | 11 | 2,001 | 816 |
| WO | 3 | 39 | 1,696 | 15 | 1,711 | 15 | 652 | 12 | 653 | 150 | 11 | 1,478 | 233 |
| NUSC | | | | | | | | | | | | | |
| NPT | 8 | 104 | 4,784 | 18 | 4,802 | 40 | 1,840 | 36 | 541 | 400 | 0 | 2,817 | 1,985 |
| NLN | 8 | 104 | 4,791 | 24 | 4,815 | 40 | 1,843 | 36 | 700 | 400 | 0 | 2,979 | 1,836 |
| NWC | 9 | 117 | 7,696 | 18 | 7,714 | 45 | 2,960 | 36 | 821 | 450 | 0 | 4,267 | 3,447 |
| SO | 5 | | | | | | | 750 | 4,000 | 250 | 0 | 5,000 | (5,000) |
| TOTALS | 55 | 650 | 30,822 | 173 | 30,995 | 250 | 11,855 | 960 | 9,732 | 2,750 | 47 | 25,344 | 5,651 |

Assumptions:

| | |
|---|---|
| Support organization | One man-year/work station |
| 2.6:1 productivity increase | Enough work |
| 5-year system life | Maintenance cost $10K/work station/year |
| Constant FY 78 dollars | Constant support cost |

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 4

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 8 | 99 | 4,899 | 24 | 4,923 | 49.5 | 2,450 | 32 | 780 | 400 | 0 | 3,662 | 1,261 |
| NCSC | 5 | 86.25 | 2,500 | 73 | 2,573 | 43.5 | 1,257 | 20 | 406 | 250 | 0 | 1,933 | 640 |
| NOSC | 10 | 117.5 | 3,800 | 20 | 3,820 | 58.8 | 1,900 | 40 | 0 | 250 | 50 | 2,140 | 1,580 |
| NSRDC | 10 | 150 | 7,500 | 30 | 7,530 | 75.0 | 3,750 | 50 | 700 | 500 | 0 | 5,100 | 2,530 |
| NSWC | | | | | | | | | | | | | |
| DL | 9 | 111 | 4,781 | 30 | 4,811 | 46.5 | 2,003 | 30 | 646 | 400 | 20 | 3,099 | 1,712 |
| WO | 5 | 71.3 | 3,100 | 25 | 3,125 | 31.5 | 1,370 | 20 | 653 | 250 | 18 | 2,311 | 814 |
| NUSC | | | | | | | | | | | | | |
| NPT | 17 | 147 | 6,762 | 38 | 6,800 | 80 | 3,680 | 77 | 541 | 850 | 0 | 5,148 | 1,652 |
| NLN | 22 | 235 | 10,825 | 67 | 10,892 | 128 | 5,900 | 100 | 700 | 1,100 | 0 | 7,800 | 3,092 |
| NWC | 24 | 240 | 15,787 | 48 | 15,835 | 120 | 7,894 | 96 | 821 | 1,200 | 0 | 10,011 | 5,824 |
| SO | | | | | | | | | | | | | |
| TOTALS | 110 | 1,257.1 | 59,954 | 355 | 60,309 | 632.8 | 30,204 | 465 | 5,247 | 5,200 | 88 | 41,204 | 19,105 |

Assumptions:

- *No support organization*
- 2.0:1 productivity increase
- 5-year system life
- *Constant FY 78 dollars*
- **Maintenance cost** $10K/work station/year
- Constant support cost

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 5
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 8 | 80 | 3,959 | 24 | 3,983 | 40 | 1,979 | 32 | 780 | 400 | 0 | 3,191 | 791 |
| NCSC | 5 | 50 | 1,449 | 73 | 1,522 | 25 | 725 | 20 | 406 | 250 | 0 | 1,401 | 122 |
| NOSC | 10 | 100 | 3,234 | 20 | 3,254 | 50 | 1,617 | 40 | 485 | 500 | 50 | 2,692 | 562 |
| NSRDC | 10 | 100 | 5,000 | 30 | 5,030 | 50 | 2,500 | 50 | 700 | 500 | 0 | 3,750 | 1,280 |
| NSWC | | | | | | | | | | | | | |
| DL | 9 | 90 | 3,876 | 30 | 3,906 | 45 | 1,938 | 30 | 646 | 450 | 20 | 3,084 | 822 |
| WO | 5 | 50 | 2,174 | 25 | 2,199 | 25 | 1,087 | 20 | 653 | 250 | 18 | 2,028 | 171 |
| NUSC | | | | | | | | | | | | | |
| NPT | 17 | 170 | 7,820 | 38 | 7,858 | 85 | 3,910 | 77 | 541 | 850 | 0 | 5,378 | 2,480 |
| NLN | 22 | 220 | 10,134 | 67 | 10,201 | 110 | 5,067 | 100 | 700 | 1,100 | 0 | 6,967 | 3,234 |
| NWC SO | 24 | 240 | 15,787 | 48 | 15,835 | 120 | 7,894 | 96 | 821 | 1,200 | 0 | 10,011 | 5,825 |
| TOTALS | 110 | 1,100 | 53,434 | 355 | 53,789 | 550 | 26,717 | 465 | 5,732 | 5,500 | 88 | 38,502 | 15,287 |

Assumptions:

- No support organization
- 2.0:1 productivity increase
- 5-year system life
- Constant FY 78 dollars
- One man-year/work station
- Enough work
- Maintenance cost $10K/work station/year
- Constant support cost

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 6
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 7 | 70 | 3,464 | 21 | 3,485 | 35 | 1,732 | 28 | 780 | 350 | 0 | 2,890 | 595 |
| NCSC | 4 | 40 | 1,159 | 58 | 1,218 | 20 | 580 | 16 | 406 | 200 | 0 | 1,202 | 16 |
| NOSC | 9 | 90 | 2,911 | 18 | 2,929 | 45 | 1,455 | 36 | 485 | 450 | 45 | 2,471 | 457 |
| NSRDC | 9 | 90 | 4,500 | 26 | 4,526 | 45 | 2,250 | 43 | 700 | 450 | 0 | 3,443 | 1,083 |
| NSWC | | | | | | | | | | | | | |
| DL | 8 | 80 | 3,446 | 27 | 3,472 | 40 | 1,723 | 27 | 646 | 400 | 18 | 2,813 | 659 |
| WO | 4 | 40 | 1,739 | 20 | 1,759 | 20 | 870 | 16 | 653 | 200 | 14 | 1,753 | 6 |
| NUSC | | | | | | | | | | | | | |
| NPT | 15 | 150 | 6,900 | 34 | 6,934 | 75 | 3,450 | 68 | 541 | 750 | 0 | 4,809 | 2,125 |
| NLN | 18 | 180 | 8,291 | 55 | 8,346 | 90 | 4,146 | 82 | 700 | 900 | 0 | 5,828 | 2,519 |
| NWC SO | 18 | 180 | 11,840 | 36 | 11,876 | 90 | 5,920 | 72 | 821 | 900 | 0 | 7,713 | 4,163 |
| TOTALS | 92 | 920 | 44,251 | 294 | 44,545 | 460 | 22,125 | 387 | 5,732 | 4,600 | 77 | 32,921 | 11,623 |

Assumptions:

No support organization
2.0:1 productivity increase
5-year system life
Constant FY 78 dollars
One man-year/work station
Enough work
Maintenance cost $10K/work station/year
Constant support cost

NAVY LABORATORY INTERACTIVE GRAPHICS STUDY
PLAN 7
(Derived from Plan 4)

| Laboratory | Work stations | Manual labor (M-Y) | Manual labor cost ($K) | Other manual cost ($K) | Total manual cost ($K) | CAD labor (M-Y) | CAD labor cost ($K) | CAD material ($K) | CAD indirect labor ($K) | CAD maintenance ($K) | CAD other ($K) | CAD total ($K) | Difference manual vs CAD ($K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADC | 4 | 40 | 1,979 | 12 | 1,991 | 20 | 990 | 16 | 780 | 200 | 0 | 1,986 | 6 |
| NCSC | 3 | 30 | 870 | 44 | 913 | 15 | 435 | 12 | 406 | 150 | 0 | 1,003 | (89) |
| NOSC | 5 | 50 | 1,617 | 10 | 1,627 | 25 | 809 | 20 | 485 | 250 | 25 | 1,589 | 39 |
| NSRDC | 5 | 50 | 2,500 | 15 | 2,515 | 25 | 1,250 | 25 | 700 | 250 | 0 | 2,225 | 290 |
| NSWC | | | | | | | | | | | | | |
| DL | 5 | 50 | 2,154 | 17 | 2,170 | 25 | 1,077 | 17 | 646 | 250 | 11 | 2,001 | 170 |
| WO | 3 | 30 | 1,304 | 15 | 1,319 | 15 | 652 | 12 | 653 | 150 | 11 | 1,478 | (159) |
| NUSC | | | | | | | | | | | | | |
| NPT | 8 | 80 | 3,680 | 18 | 3,698 | 40 | 1,840 | 36 | 541 | 400 | 0 | 2,817 | 881 |
| NLN | 8 | 80 | 3,685 | 24 | 3,709 | 40 | 1,843 | 36 | 700 | 400 | 0 | 2,979 | 731 |
| NWC SO | 9 | 90 | 5,920 | 18 | 5,938 | 45 | 2,960 | 36 | 821 | 450 | 0 | 4,267 | 1,671 |
| TOTALS | 50 | 500 | 23,709 | 173 | 23,882 | 250 | 11,855 | 210 | 5,732 | 2,500 | 47 | 20,344 | 3,538 |

Assumptions:

No support organization
2.0:1 productivity increase
5-year system life
Constant FY 78 dollars

One man-year/work station
Enough work
Maintenance cost $10K/work station/year
Constant support cost

# Appendix E
## COST SENSITIVITY ANALYSIS

The same assumptions that were used to calculate the alternative plans in Appendix D were used in the sensitivity analysis. The productivity is the only item that was changed. A summary of the sensitivity analysis is given below. Since the support organization was considered only in Plans 1, 2, and 3, the dollar savings for these three plans are shown.

Cost Sensitivity Analysis Summary

| Productivity | Cost savings* ($M) | | |
|---|---|---|---|
| | Plan 1 | Plan 2 | Plan 3 |
| 2.0 | 10.3 | 6.6 | (1.5) |
| 2.1 | 13.0 | 8.8 | (0.3) |
| 2.2 | 15.6 | 11.0 | 0.9 |
| 2.3 | 18.3 | 13.3 | 2.1 |
| 2.4 | 21.0 | 15.5 | 3.3 |
| 2.5 | 23.6 | 17.7 | 4.5 |
| 2.6 | 26.3 | 19.9 | 5.7 |
| 2.7 | 29.0 | 22.1 | 6.8 |
| 2.8 | 31.7 | 24.3 | 8.0 |
| 2.9 | 34.3 | 26.5 | 9.2 |
| 3.0 | 37.0 | 28.7 | 10.4 |
| 3.5 | 50.4 | 39.8 | 16.3 |
| 4.0 | 63.7 | 50.9 | 22.2 |
| 5.0 | 90.4 | 73.0 | 34.1 |

*Savings does not include equipment cost.

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